A Study on Thermal behavior of Nano film as thermal interface layer

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Abstract — **Increase in thermal design power and reduce in manufacturing cost of the processor chip has pushes the need for high performance and durable test fixture design in future. Test fixture with efficient themal management has lowest resistance possible to maintain the accuracy of the device temperature when it makes contact with processor chip's silicon during test. High thermal conductivity and mechanical reliability of text fixures are desired for high volume test environment. Nano film materials such as Aluminum Titanium Nitride (AlTiN), Titanium carbide (TiC), Titanium on Titanium nitride (Ti on TiN), Titanium nitride on Titanium (TiN on Ti) and Aluminum(III) Oxide (Al2O3) are coated over copper substrates by Filtered Cathodic Vacuum Arc (FCVA) deposition method and tested for their thermal conductivity behavior for high volume test (HVM) environment. Thermal conductivity of the prepared films is tested by using the ASTM 5470 Thermal Interface Material (TIM) Tester. Titanium on Titanium nitride (Ti on TiN) and Aluminum (III) Oxide (Al2O3) observed with highest thermal conductivity of 117.68 W/mk and 128.34 W/mk respectively among the prepared nano thin films. Thickness of the film and stack configuration influenced the thermal conductivity of the prepared film.**

***Keywords* - nanoflim; thermal conductivity; thermal management; thermal contact resistance**

I. INTRODUCTION

The continuous increase of power dissipation in processor chip has pushed the limit of thermal mangement to a more precise determination of heat flow behavior. The International Technology Roadmap for Semiconductors (ITRS) reported the expected power density and junction-to-ambient thermal contact resistance for high-performance chips at 14 nm generation as > 100 W/cm^2 and < 0.2°C/W, respectively [1]. The text fixture in which the thermal resistance between the fixture pedestal and processor chip's silicon should be low in order to reduce the junction-to-ambient thermal resistance for quality electronic products. As per the ITRS 2007 road map, the total power of a cost performance single chip is expected to achieve 173 Watts/cm^2 in 2022 [1]. In addition to thermal performance, the cost factor such as manufacturing and test process for the processor chip should satisfy the requirement of the need as per the Moore's Law prediction [2]. The overall resistance in heat transfer network must be reduced to maintain heat sensitive components, such as silicon die junction's temperature, at or below safe operating temperatures during test condition. When two real flat metal surfaces make in contact, the thermal interface is formed with many discrete micro contact spots.

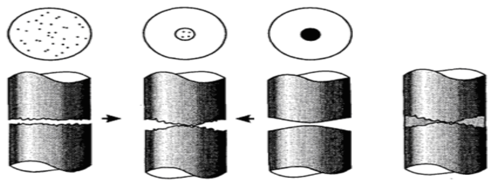

Fig. 1: Contacting surface geometries

When two real flat metal surfaces make in contact, the thermal interface is formed with many discrete micro contact spots. The thermal interface resistance could be reduced by filling the gap in-between the two real surfaces by using high thermal conductivity material. It is necessary to test the processor chip at extreme condition (-40C and 110C) for planning the thermal management and power dissipation at high volume manufacturing test environment. Fig.2 illustrates the Test tooling design with pedestal contact on processor chip's silicon. Belady [3] reported the influence of increasing package power on the size and design of the semiconductor electronic components. She also reported the issues of semiconductor cooling as well as some of the current and emerging cooling solutions in her study. In order to overcome the thermal management rising risk, a new contact surface with high thermal conductivity and durability is needed. High quality particle free coatings have been successfully employed for increasing the wear resistance of precision stamping dies and also in production tool coating [4-6].

The rms roughness is decreased dramatically when the macro particle content is reduced [7]. Metallic coatings provide modest to significant thermal enhancement, depending upon the metal used and the method of application. They are also provide modest to excellent thermal isolation depending upon the choice of material. Metallic coatings are free of the contamination problems associated with thermal greases and the handling problems associated with soft foils. Jindal et al. [8] had investigated the properties and performance of TiAlN, TiCN and TiN PVD-coated tungsten carbide tool. They had found that TiAlN coating had better adhesion properties than TiCN, where TiCN possessed higher residual stress that caused slips of the

coating. In our study, all nitride coatings were prepared by filtered arc vacuum deposition method. The properties of FAD TiN films are determined principally by the deposition parameters of substrate bias, temperature and reactive gas pressure [9]. In this paper, the thermal conductivity of nitride nano coatings prepared on copper pedestal test fixture is calculated and the observed results are reported here.

II. THEORETICAL BACKGROUND

From the heat conduction Fourier's law [10], time rate of heat transfer through a material is proportional to the negative gradient in the temperature and to the area. The differential form of Fourier's Law of thermal conduction shows that the local heat flux, $\vec{q}$ is equal to the product of thermal conductivity, k, and the negative local temperature gradient, $-\nabla T$. The heat flux is the amount of energy that flows through a particular surface per unit area per unit time, (1) as follow:

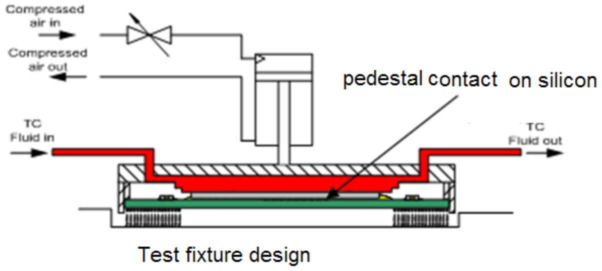

Fig 2: Schematic illustration of test contact surface

$$\vec{q} = -k\nabla T \qquad (1)$$

Where (including the SI units) $\vec{q}$ is the local heat flux, W·m^{-2}, k is the material's conductivity, W·m^{-1}·K^{-1}, ∇T is the temperature gradient, K·m^{-1}. For many simple applications, Fourier's law in one-dimensional form can be described by (2)

$$q_x = -k\frac{dT}{dx} \qquad (2)$$

Rearranging the equation 2, and substitute the heat flux as Q, temperature gradient as T_H and T_C are temperature on the hot and cold side respectively, the effective thermal conductivity k_{eff} of the system in one dimension which is along the axial axis of the sample can be represent by (3).

$$k_{eff} = \frac{\dot{Q} \times l_t}{(T_H - T_c)} \qquad (3)$$

Where l_t and A are total thickness of sample and contact area of sample. From the actual sample, the contact pedestal is coated with nanoflim as illustrate in Fig. 3, the total thermal conductivity of the sample can be calculated by using (4)

$$k_{eff} = \frac{k_1 k_2}{k_1 l_2 + k_2 l_1} \times \qquad (4)$$

k_{eff} is the total thermal conductivity of the sample, k_1 and k_2 are thermal conductivities of nanoflim layer and copper base respectively, lt is the total thickness of the sample, while l_1 and l_2 are the thicknesses of nanoflim layer and copper base. This equation considers the total thermal conductivity of a two layer and assumes contact area of the top and bottom surfaces of to be the equal in magnitude and without asperities. Under the control experiment environment, l_2, k_2 is constant across all the samples, the effective thermal conductivity k_{eff} observed from the experimental data will be represent the influence on the nanoflim thermal conductivity k_1 given a known coating thickness to the overall thermal conductivity improvement. The nano flim thermal performance can be estimated in a relative comparison basic.

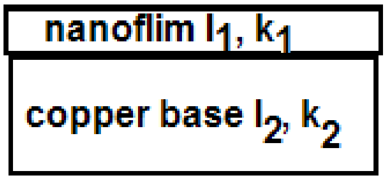

Fig. 3: Nanoflim coated on copper base Pedestal

III. EXPERIMENTAL METHOD

A. Nano film coating

In this study, various nano film coating is used and the list is given in Table 1. Nano film samples are prepared over copper substrates with thickness of 3.5 mm by using Filtered Cathodic Vacuum Arc (FCVA) deposition [11]. FCVA technology has the capability of producing large area of ultra pure metal coating with an excellent uniformity and has consistent low resistivity close to that of a bulk material. Unwanted macro particles and neutrals are then be filtered out by a cross-magnetic and electric field. Only ions within a well-defined energy range are allowed to reach the substrate.

B. Thermal conductivity of nano films

The thermal conductivity of the nanoflim coating under various pressures at fixed heat load is tested by using standard control lab environment with ASTM standard 5470 TIM tester. Before the samples are sandwiched between a heater and cooler plate, both the heater and cooler surfaces are well cleaned and the temperature is maintained at 15 ˚C by flowing water at the flow rate of 6 litres per minute. Surface cleaning should be done in order to remove and remnants from previous measurements. Cooling plate has to be wiped to remove water condensates.

The required pressure from 100 to 1100 KPa for measurementis applied over the sample once heating plate made contact with the sample. The heater starts to provide the heat to the top surface of the samples. The heating process continues until the steady state condition reached. In order to get the stable heat flux, current and voltage of the heater is adjusted to keep constant. Once the steady state heat flux is achieved, the data from the thermocouples, LVDT is recorded and the thermal resistance and apparent thermal conductivity of the thin film samples are calculated using the equation 4. Overall thermal conductivity of samples is measured at various pressures ranging from 100kPa to 1100kPa. Measurements are only made once sample is allowed to cool for a while to avoid sample damage from continuous heat cycling and heat shock. The increment in applied pressure is maintained as 200 KPa. Prior to do the experiment on thermal conductivity of thin films, calibration should be performed to ensure the performance of metrology tools as per the ASTM5470 standard. Fig. 4 shows the schematic diagram of thermal conductivity measurement for nitride coatings using ASTM5470 standard.

TABLE I LIST OF NANO FILM COATING AND THEIR THICKNESS

Nanoflim composition	Thickness
AlTiN	0.5um
TiC	0.5um
Ti on TiN	0.5um/0.5um
TiN on Ti	0.5um/1.0um
TiN on Ti	0.5um/0.5um
Al_2O_3	0.5um
Al_2O_3	1.0um

C. *Equipment calibration*

Thickness gauge calibration is the first step before any experiment is performed. This is to eliminate zero error in the thermal conductivity measurement with respect to the overall sample thickness. This is bone by dropping a single drop of water onto the center of the stage of the TIM tester and lowering the hot plate. Thermocouples calibration is then carried out as second step. There are three thermocouples in the TIM tester, there are located on the hotplate, side surface of the sample and the cold plate. The thermocouples used in the TIM tester are T type thermocouple which is a copper constantan thermocouple.

The thermocouple simulator Eurotron Unical Tc is use to force a simulated temperature value to the tester and compares to the recorded value. Each values and variations are recorded and compensation to the thermocouple will be made automatically by the software until its meet the variation of smaller than 0.1%. Last calibration procedure is to ensure the Current I, and Potential difference V, of the system is calibrated for an accurate heater power read out.

Heat generated by the system can be obtained by product of Current with Potential difference, $P = VI$ for electrical heaters. Therefore the values for current and potential difference have to be measured for better and accurate measurements. This calibration is similar to the thermocouple calibration, but utilizes a digital multimeter instead. A calibration rig is connected to the TIM tester and the computer system. The multimeter is connected to the calibration rig and the value recorded by the computer is compared to the value recorded by the multimeter. Any compensation required will be entered to the tester software until its meet the variation of smaller than 0.1%.

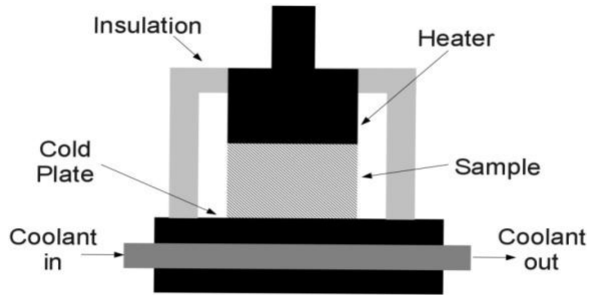

Fig. 4 Experimental Setup using TIM Tester

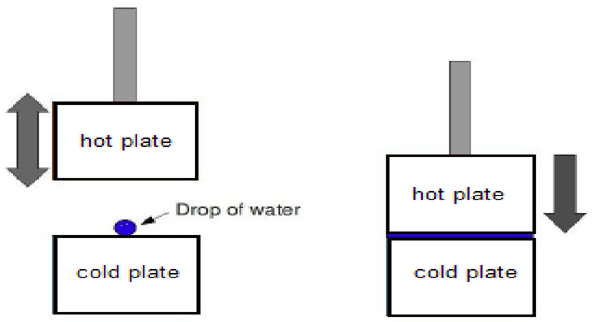

Fig. 5 Thickness gauge calibration procedure

IV. RESULTS AND DISCUSSION

The surface morphology of the coated TiN and TiC nano thin film is recorded and presented in Fig. 6(a) & (b). It showsthat the TiN thin film shows rough surface than TiC surface. The thermal conductivity of all nano thin film samples are measured using ASTM standard 5470 TIM tester and calculated values are plotted in Fig.7.

Apparently, all sample showed higher thermal conductivity when subjected to 1100 Kpa pressure, however highest effective thermal conductivity could be observed for Al_2O_3 with 1μm thickness than all other nanoflim sample tested. Although the effective thermal conductivity is calculated with inclusive of contact resistance between the contact surfaces, the effect of thermal resistance can be decouple with all samples are subject to the exact same test condition. Fig. 8 reveals the influence of thickness on the thermal conductivity of Al_2O_3 nano thin film and shows high value for higher thickness measured at high pressure (1000 KPa).

It is attributed to the facts that an increase in micro

contact at the contact surface under higher interfacial pressure [12]. Normally, the deformation occurs at the contact surface when apply load on that surface and hence the contact surface area increases [13, 14]. This deformation may either plastic or elastic, depending on the material properties and the contact pressure. In addition, Fig. 9 also clearly indicates that the thickness of Ti also influences the thermal conductivity of TiN coating. It shows that higher Ti thickness helps to improve the thermal conductivity of TiN drastically (3 times) but noticeable increment on thermal conductivity could also be observed for changing the film stack configuration from TiN/Ti to Ti/TiN (see Fig.7) for all applied load except 200 KPa. This may be due to the thermal mismatch of Ti on Cu substrates.

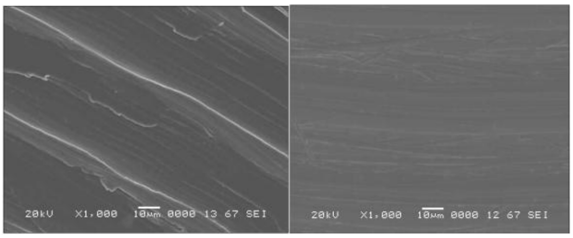

Fig. 6 SEM image of (a) TiN and (b) TiC recorded at 1000x magnification

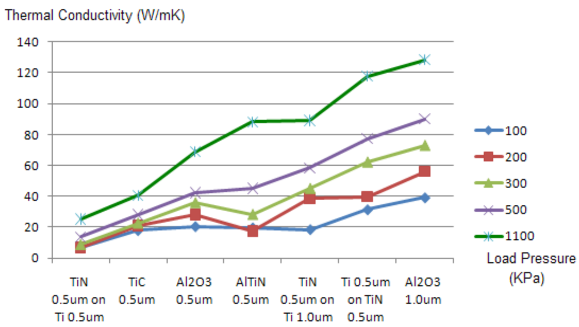

Fig. 7 Calculated thermal conductivity of nano films with respective to applied load

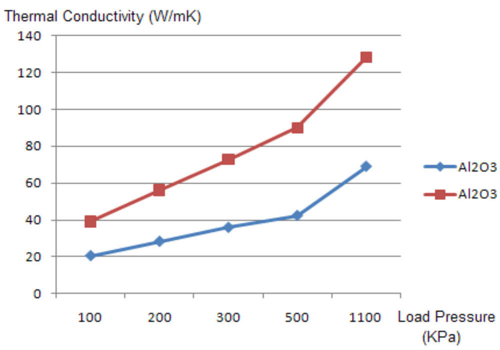

Fig. 8 Influence of thickness on thermal conductivity of Al_2O_3 for various pressures

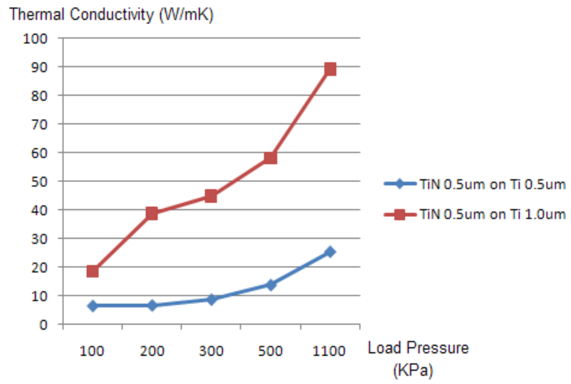

Fig. 9 Influence of thickness on thermal conductivity of Al_2O_3 for various pressures.

From the Fig.7, it is also noticed that the nano films such as TiC and AlTiN shows low thermal conductivity as with applied load varies in between 100 to 500 KPa. It seems to the influence of applied load on increasing thermal conductivity as low when compared to other nano film coatings.

V. CONCLUSION

Various nano films were on copper substrates and their thermal conductivity was measured using ASTM standard 5470. Al_2O_3 based nano films showd good thermal conductivity at high applied load than other samples. Increased thermal conductivity was observed for higher film thickness. Film stack configuration was also affected the observed thermal conductivity. Effective thermal conductivity data shows promising result in applying wear resistance coating on tooling contact pedestal as a thermal interfacial material.

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